A Scenario-based Transmission Network Expansion Planning in Electricity Markets

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***Abstract*—It is important to handle the transmission network expansion planning problem under restructured power systems to allow fair competition in the system. A scenario-based two-stage Transmission Network Expansion Planning (TNEP) is presented in the paper and solved using a meta-heuristic algorithm. Various scenarios, for market-driven power flow patterns is considered in a 6-bus Garver Test System, and Differential Evolution is employed to solve the traditional Transmission Network Expansion planning problems in each scenario. A decision making scheme based on risk analysis is employed to select a plan with minimum risk. In this paper it is assumed that the market players trade only via pool market model, where bid pricing affects the generator loading.**

I. INTRODUCTION

Transmission grid is the key agent in giving all the market participants fair access to supply or consume energy. It is desirable that the transmission network provides to all the participants a level economic playground for trade [1]. This robust network will attract market participants from distant areas to compete in the power market and help in eliminating dominant generator pockets in grid. There had been several delays in needed transmission network expansion in Australia, for achieving the optimality in network plan in past [1]. Conventional transmission network planning is a large -scale, mixed integer, non convex optimization problem that addresses the problem of network broadening and strengthening to serve the growing electricity market. Most of the literature deals with the Transmission Network Planning problem in a monopolistic market perspective which are not very suitable for restructured power systems [2], [3], [4] and only recently focus has come to network planning in restructured power systems. Several solution techniques like, branch-and-bound, sensitivity analysis, and linear programing, have been used in literature to solve the network expansion problem. Apart from these many meta-heuristic algorithms like Genetic Algorithm (GA) [5], Harmony Search (HS) [2], Tabu Search [6] and Particle Swarm Optimization (PSO) [4] [7] have been used to solve the traditional TNEP. This paper focuses on solving a TNEP problem on a restructured power system using Differential Evolution (DE) for a Garver Test System. It might be very well stressed that Garver System being a small test system, this problem does not require a powerful tool like Differential Evolution. The aim of the paper here is to show the applicability of DE in form of a tool to solve such a TNEP problem and formulation of a two stage scenario based TNEP problem for restructured power system environment.

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This paper exploits the impact of competitive environment in power system to identify scenarios that are attributed to dominant power flow patterns in grid. It is seen that in competitive environment due to open access and bidding, the power flow patterns could change frequently and drastically. As a result some power flow patterns could have not been predicted and looked for in the traditional TNEP. Every scenario might lead to a different bottle-neck line and traditional TNEP might lead to an unsatisfactory result. It could result in loss of load in certain scenarios to meet the line flow constrains during operation. There has to be a trade off between the investment cost and the cost of energy not served if a plan is not satisfactory for some scenario to reduce risk, and this trade off shall be implied through out the operational period and depends on the predicted time for which each scenario occurs in the forecast. This could be shown in terms of an occurrence probability for each scenario. The key step in such a planning formulation is identification of seriously variant and repeatedly occurring scenarios. The identification of these could be achieved using Monte-Carlo simulator dealt in [8].

II. PROBLEM DEFINITION

The process of TNEP under restructured system discussed in this paper is divided into four stages:

- Scenario Identification
- Traditional Transmission Network Expansion planning for each scenario
- Calculate loss of load, and Cost of energy not served in each plan for various scenarios
- Decision making step to select one of the plans, with trade-off between investment cost and cost of energy not served.

The whole process is summarized in the following block diagram in figure 1. For the purview of this paper he Scenario generation step is not dealt with and we assume the scenarios and their occurrence probabilities. This step could be achieved with the Monte carlo simulator mentioned in last section. The later steps of Traditional TNEP and Loss of Load calculation are formulated and solved using Differential evolution.

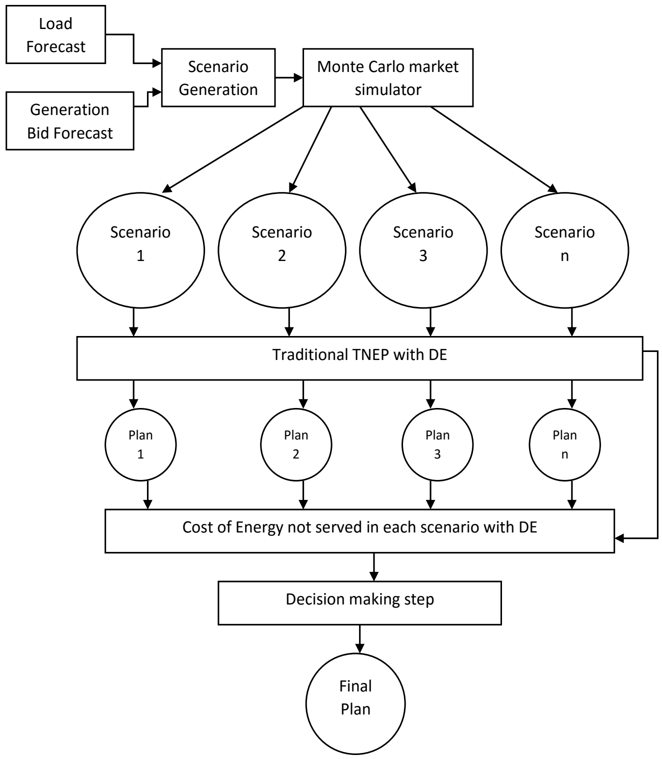

Fig. 1. Block Diagram for Scenario-based TNEP

The last step of decision making is discussed in three different ways, a regret matrix analysis appearing in [1], a novel weighted sum analysis, and a union plan method for high reliability of system. The plan achieved on test system by all the three decision making methods is discussed in the paper.

III. Problem Formulation

A. Traditional Transmission Network Expansion Planning

The traditional TNEP with DC load flow as formulated in [1], [3] is followed and is shown below.

$$minimize : v_{plan} = \sum_{i,j} c_{ij} n_{ij} \tag{1}$$

subject to the following constraints:

$$s^T f + g = d \tag{2}$$
$$f_{ij} - (\gamma_{ij}^o + x_{ij})(\theta_i - \theta_j) = 0 \tag{3}$$
$$|f_{ij}| - x_{ij}\overline{\phi_{ij}} \leq \gamma_{ij}^o \overline{\phi_{ij}} \tag{4}$$
$$\overline{\phi_{ij}} = \overline{f_{ij}} / \gamma_{ij}^o \tag{5}$$
$$0 \leq g \leq \overline{g} \tag{6}$$
$$x_{ij} = n_{ij}\gamma_{ij} \tag{7}$$
$$0 \leq n_{ij} \leq \overline{n_{ij}} \quad \forall (i,j) \in \Omega \tag{8}$$
$$n_{islands} = 0 \tag{9}$$

where, c_{ij} is the cost of adding a new line in corridor $i-j$, $n_{i,j}$ is the number of new lines added in corridor $i-j$, s is the node-branch incidence matrix, f is the vector containing active power flows through lines as its elements, g is vector for generated active power, d is the vector of forecasted load, x_{ij} is the total susceptance of new lines added in corridor $i-j$, γ_{ij}^o is the initial susceptance of all the lines existing in corridor $i-j$, θ_i is the voltage angle at bus i, $\overline{f_{ij}}$ is the maximum power flow limit on line in corridor $i-j$, γ_{ij} is the new line susceptance in corridor $i-j$ for a single line, $\overline{g}$ is the vector for maximum generation limits, $\overline{n_{ij}}$ is the maximum number of new lines that can be added in the corridor $i-j$, and Ω is the set of all candidate circuits in system. Equation 2 and 3 represent the power balance equations in circuit and DC load flow equations in system respectively, equation 4 represents the maximum power flow limit in corridor $i-j$, equation 9 shows the constraint to eliminate any islanded buses in the system, and equation 8 refers to the upper limit of new lines addition in corridor $i-j$.

B. Optimal Load Shedding

This step comes once the plan for each scenario is achieved and its optimality for other scenarios is to be checked. We assume that there is a pool model trading in grid and all the load is cleared at Marginal Price. In case a particular plan shows an overflow then the load in system are reduced, and the optimization is aimed at minimizing the total load curtailment. On the generation side, total load curtailment is reflected in proportional reduction in generation levels of that particular scenario under study. This comes form the fact that only pool trading is considered here and the generation schedules would differ if there were bilateral transactions involved. Thus it would turn into an optimization problem for each plan under each scenario as below [1]:

$$minimize \ w_{t,plan} = \sum_i r_{t,i} \tag{10}$$

subject to:

$$s^T f + g' = d' \tag{11}$$
$$f_{ij} - (\gamma_{ij}^o + x_{ij})(\theta_i - \theta_j) = 0 \tag{12}$$
$$|f_{ij}| - x_{ij}\overline{\phi_{ij}} \leq \gamma_{ij}^o \overline{\phi_{ij}} \tag{13}$$
$$\overline{\phi_{ij}} = \overline{f_{ij}} / \gamma_{ij}^o \tag{14}$$
$$d_i' = d_i -_i r_{t,i} \tag{15}$$
$$g_i' = g_i - \frac{g_i}{\sum_i (g_i)} \times \sum_i r_{t,i} \tag{16}$$

where, s, f, γ_{ij}^o, $\overline{f_{ij}}$, θ_i and g take the usual notions as in section III-A, g' is the new generation vector having the reduced generation at each bus as its elements, the reduced generation at each bus is calculated using equation 16, g_i and d_i are initial generation and demand schedule at each bus, while g_i' and d_i' are the new generation and demand schedule at each bus after load curtailment, $r_{t,i}$ is the load curtailment at bus i in scenario t.

C. Decision Making step

There are three decision making step discussed here:

- Weighted sum analysis
- Regret matrix analysis
- Union plan

1) Weighted Sum Analysis: In this case the plan is selected that has the least weighted sum of total investment cost and cost of energy not served across all scenarios.

$$selected\ plan = min_{plan}\{(v_{plan} + \sum_{t}(p_t \times w_{t,plan}))\} \tag{17}$$

where, p_t is the probaility of scenario t to occur, v_{plan} is the investment cost of plan, $w_{t,plan}$ is the cost of energy not served.

2) Regret Matrix Analysis: The regret matrix analysis was proposed by Fang and Hill in 2003 [1], and proposes the following method:

- calculate the value of attribute for each plan-future pair:

$$a_{i,t} = a(pl_i, fu_t) \tag{18}$$

where, pl_i is the candidate plan i, and fu_t is the future scenario t, and the attribute is defined as sum of investment cost of plan and cost of energy not served in scenario t with plan i.

- Calculate measure of risk called regret:

$$regret_{i,t} = a_{i,t} - a_{opt,t} \tag{19}$$

where, $a_{i,t}$ is the attribute of plan i in scenario t, and $a_{opt,t}$ is the optimal plan for scenario t achieved by solving traditional TNEP on scenario t.

- The final plan is selected based on the following decision making equation:

$$selected\ plan = min_i(max_t(p_t \times regret_{i,t})) \tag{20}$$

3) Union Plan: This method is proposed to be useful when highly reliable system is required and cost of energy not served is very high, or in other workds, loss of load is not tolerable. In this case the final plan is given as:

$$selected\ plan = \cup_t\{plan_{opt,t}\} \tag{21}$$

where, $plan_{opt,t}$ is the optimal plan for scenario t.

IV. Differential Evolution

Differential Evolution [9] [10] is implemented to optimize the sub-problems mentioned in section III-A and III-B. It is a real valued, continuous domain optimization algorithm that is implemented to solve any complex multi-dimensional optimization problem. Differential Evolution has appeared numerous times in literature to solve the TNEP effectively and is only held in this paper as a tool for optimization. No efforts have been made here for superiority of this algorithm but its applicability and feasibility is definitely established as has been done at numerous occasions in past.

It is an optimization strategy to maximize or minimize any given multi-dimensional function [11]. In every iteration recombination and selection is done on population to get a new population which is called as generation. Recombination is a key step where child population is created from the members of the parent population, and selection is the step where decision is made as to which members of the parent and child population are going to be promoted into next generation. Recombination is achieved by adding the difference between two randomly chosen coordinates to a member of the parent population. The crossover factor generally varies between 0.2 to 0.8. A lower crossover constant results into a very similar parent -child population scenario, whereas larger child population will cause very different child populations [10]. The mutation weight λ is a weight that determines to what extent the difference in the random coordinates will affect the member of parent population to give rise to a child population. Large mutation weight will ensure convergence to a global maxima or minima while a low mutation weight will decrease time of convergence. The various recombination equations are listed as follows:

$$x_i^c(j) = x_i^p(j) + \lambda.(x_i^p(R1) - x_i^p(R2)) \tag{22}$$

$$x_i^c(j) = x_i^{best} + \lambda.(x_i^p(R1) - x_i^p(R2)) \tag{23}$$

$$x_i^c(j) = x_i^p(j) + \lambda.(x_i^{best} - x_i^p(j)) + \lambda.(x_i^p(R1) - x_i^p(R2)) \tag{24}$$

where, $x_i^p(j)$ and $x_i^c(j)$ represent the ith coordinate of the jth member of the parent and child population respectively, and x_i^{best} is the ith coordinate of the best vector in all the generations. These three distinct recombination equation are different DE schemes in literature and called as DE1, DE2 and DE3 for equation 22, 23, 24 respectively. In this paper DE3 has been used for all optimization sub problems. A flow chart of DE when implemented to solve an optimization problem is shown in figure 2.

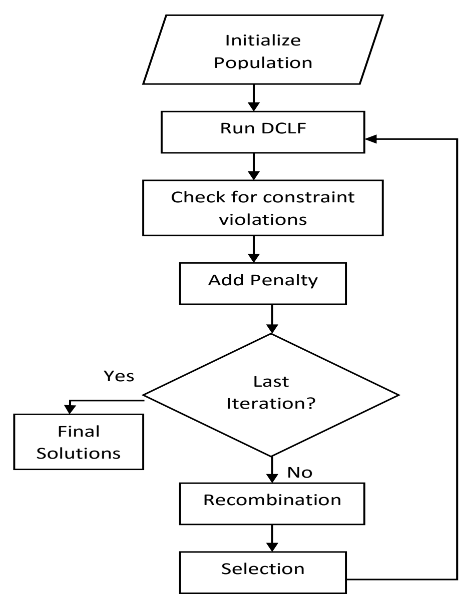

Fig. 2. Flow Chart for Differential Evolution

V. Test System Considered

The test system considered is a 6 bus Garver System which happens to be a standard for TNEP problem. The initial configuration for Garver test system is taken form [12]. Four scenarios are considered as a part of analysis in this paper. The various load and generation levels in scenarios are mentioned in table I. To calculate the cost of energy not served in Weighted Analysis and Regret Matrix Methods a penalty of $\$1000/MW$ of lost load is considered for the total planning period. The scenarios are identified through a forecasted load and bids in a Monte Carlo simulator, and is not in the scope of this paper. The values in the table are assumed with the aim to create a variety of power flow patterns. It could be of interest to create some more scenarios and vary the probabilities of occurrence for further study. However in a real system these scenarios would be generated through the analysis on forecasted loads. The cost of each line addition in various corridors are taken from [13].

TABLE I
Scenarios in Garver Test System

Scenarios	PG1(MW)	PG3(MW)	PG6(MW)	Probability
Scenario 1	50	165	545	0.15
Scenario 2	150	10	600	0.33
Scenario 3	150	360	250	0.25
Scenario 4	120	120	520	0.27

VI. Results and Discussion

A. Traditional TNEP in various scenarios

Differential Evolution was employed to solve the traditional TNEP in various scenarios mentioned in table I. The convergence graphs of DE while solving the traditional TNEP in various scenarios are shown in figure 3. The various plans recorded through DE are mentioned as follows:

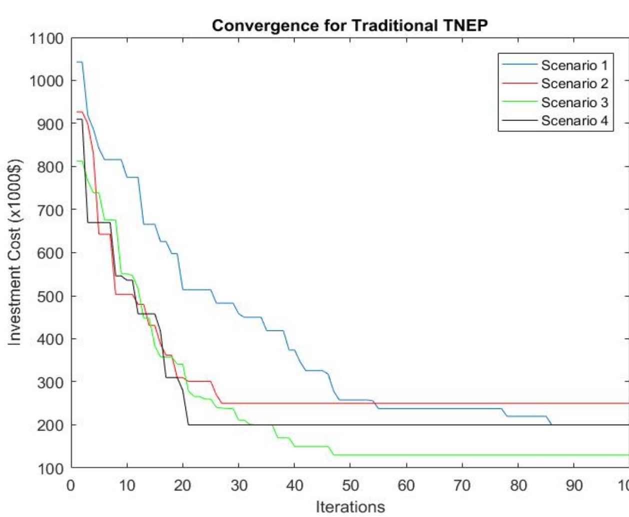

Fig. 3. Convergence with Differential Evolution

1) *Scenario 1:* $n_{2-6} = 4$, $n_{3-5} = 1$, $n_{4-6} = 2$, with a total investment cost of $\$200000$ referred to as Plan1.

2) *Scenario 2:* $n_{1-5} = 2$, $n_{2-6} = 4$, $n_{4-6} = 3$, with a total investment cost of $\$250000$ referred to as Plan2.

3) *Scenario 3:* $n_{2-6} = 3, n_{3-5} = 2$, with a total investment cost of $\$130000$ referred to as Plan3.

4) *Scenario 4:* $n_{2-6} = 4$, $n_{3-5} = 1$, $n_{4-6} = 2$, with a total investment cost of $\$200000$ referred to as Plan4.

It might be noted that a similar plan is optimal for two scenarios, Scenario 1 and Scenario 4. In some rare cases if a common plan arrives as the optimal plan for all cases then that plan is selected and there is no requirement of a decision making step.

B. Optimal load shedding in various 'plan-scenario' pairs

The optimal load curtailment as formulated in section III-B is shown in MW in table II

TABLE II
Total Load Shedding

Scenarios	Plan 1	Plan 2	Plan 3	Plan 4
Scenario 1	0	103.48	341.65	0
Scenario 2	70.93	0	380	70.93
Scenario 3	42.22	253.33	0	42.22
Scenario 4	0	27.60	321.53	0

There are 5 loads in system at buses 1-5. The load curtailment for each 'plan-scenario', to meet the constraints rounded off to two decimal places is mentioned in table III.

TABLE III
Optimal Load Shedding at each load

Plan/Scene	L1(MW)	L2(MW)	L3(MW)	L4(MW)	L5(MW)
1/1	0	0	0	0	0
1/2	0	0	34.65	0	36.28
1/3	13.96	19.77	0	2.64	5.85
1/4	0	0	0	0	0
2/1	0	0	0	0	103.48
2/2	0	0	0	0	0
2/3	29.88	53.00	0	67.21	103.24
2/4	0	0	0	0	27.60
3/1	27.31	187.65	30.73	63.90	32.06
3/2	6.54	189.49	19.78	28.34	135.85
3/3	0	0	0	0	0
3/4	4.77	184.49	1.07	46.64	84.57
4/1	0	0	0	0	0
4/2	0	0	34.65	0	36.28
4/3	2.98	15.65	0	12.62	10.96
4/4	0	0	0	0	0

It might be noted that since plans 1 and 4 are same, the load curtailments in both the plans under scenarios 3 must be the same. However DE was able to find two alternate load shedding schedules that result in equal total load curtailment but with different load curtailments at different load buses as shown in table III. On several trials such alternate solutions were recorded and both the load shedding schedules are satisfactory. In case a scenario arises when one load has more priority than the other, one load shedding schedule may be preferred over the other.

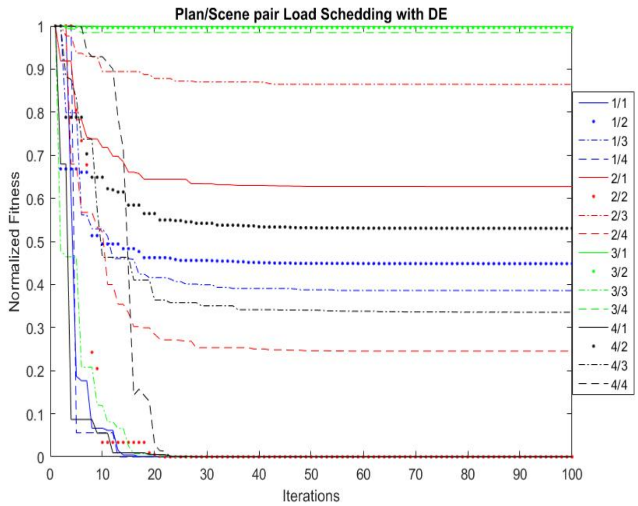

Fig. 4. Convergence for Load Shedding with Differential Evolution

The normalized convergence graphs for various Plan-Scenario pairs for load shedding problem when implemented with DE is shown in figure 4. It can be noted that the third plan causes difficulty in convergence and most of the convergence stays near the maximum value. This means Differential Evolution is not able to find a very easy load curtailment solution other than the randomly generated one. It shows the stiffness of power-flows in this plan and causes has large load curtailment to meet the line flow limits constraint.

C. Decision Making Analysis

In this section the final plan for TNEP is decided. As mentioned earlier there are three ways to decide upon the most optimal plan. Each method is discussed here.

1) Weighted Sum Analysis: Equation 17 was implemented and the final plan 1 (plan 4 is equivalent) was selected. The final weighted sum for each plan is in table IV. It can be seen that even though plan 3 had a very low investment cost it was not selected as it had high load curtailment scenarios.

TABLE IV
WEIGHTED SUM

Plans	Weighted Sum
Plan 1	233963.54
Plan 2	336306.65
Plan 3	393463.08
Plan 4	233963.54

2) Regret Matrix Analysis: Equations 18, 19 and 20 were implemented to select the final plan 1(plan 4 is equivalent). The weighted regret matrix and implementation is shown in table V. It can be seen that even though plan 3 had a very low investment cost it was not selected as it had high load curtailment scenarios.

3) Union Plan: Equation 6 was implemented to achive a final highly reliable and all scenario ready plan as follows: $n_{1-5} = 2$, $n_{2-6} = 4$, $n_{3-5} = 2$, $n_{4-6} = 3$, with a total

TABLE V
WEIGHTED REGRET MATRIX

Plan/Scene	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Max Regret
Plan 1	0	6907.99	28055.55	0	28055.55
Plan 2	23022.09	0	93333.33	20951.24	93333.33
Plan 3	40747.71	85800	0	67931.57	85800
Plan 4	0	6907.99	28055.55	0	28055.55

investment cost of $290000. There shall be no load curtailment in any scenario in this union plan.

The single line diagram of Garver system with Plan 1 and Union Plan are shown in figure 5 and figure 6 respectively. Lines shown in green color are the new additions while black lines are the existing lines.

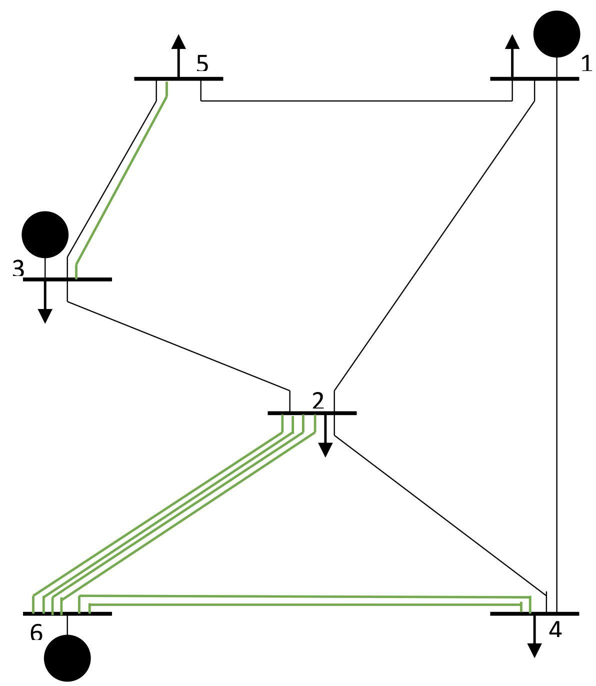

Fig. 5. Plan1 in Garver System (Best choice with Weighted sum and Regret methods)

VII. CONCLUSION

Th paper explored a scenario based transmission network expansion planning strategy under restructured environment. Differential Evolution was found to be very feasible tool to solve such a TNEP problem and could be scaled easily to larger systems. Three decision making techniques were suggested in paper. The weighted sum analysis is suggested when there are a lot of scenarios and overall performance of transmission network is more important than the instantaneous scenario specific performance, regret matrix analysis is suggested when instantaneous scenario specific performance is of concern rather than the overall performance for the total period

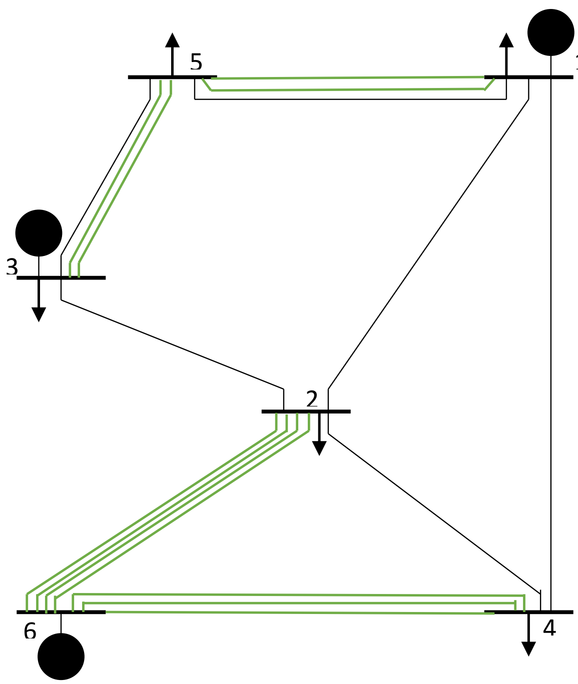

Fig. 6. Union Plan in Garver System (No load curtailment)

while union method is suggested when the grid has to avoid all the load shedding cases. The system presented in paper is useful when the trading is done in a pool market system. Scope for improvement lies when bilateral trading bids are also a included. However, weighted sum method and regret analysis method gave same results in the case studied in paper, it might not be the case for a complex system with many scenarios.

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References

[1] R. Fang and D. J. Hill, "A new strategy for transmission expansion in competitive electricity markets," *IEEE Transactions on Power Systems*, vol. 18, no. 1, pp. 374–380, Feb 2003.

[2] A. Verma, B. K. Panigrahi, and P. R. Bijwe, "Harmony search algorithm for transmission network expansion planning," *IET Generation, Transmission Distribution*, vol. 4, no. 6, pp. 663–673, June 2010.

[3] H. Seifi and M. S. Sepasian, *Electric power system planning: issues, algorithms and solutions*. Springer Science & Business Media, 2011.

[4] D. Kavitha and K. S. Swarup, "Transmission expansion planning using lp-based particle swarm optimization," in *2006 IEEE Power India Conference*, 2006, pp. 6 pp.–.

[5] M. J. Rider, I. de J. Silva, R. Romero, A. V. Garcia, and C. A. Murari, "Transmission network expansion planning in full open market considering security constraints," in *Power Tech, 2005 IEEE Russia*, June 2005, pp. 1–6.

[6] R. A. Gallego, R. Romero, and A. J. Monticelli, "Tabu search algorithm for network synthesis," *IEEE Transactions on Power Systems*, vol. 15, no. 2, pp. 490–495, May 2000.

[7] M. Eghbal, T. K. Saha, and K. N. Hasan, "Transmission expansion planning by meta-heuristic techniques: A comparison of shuffled frog leaping algorithm, pso and ga," in *2011 IEEE Power and Energy Society General Meeting*, July 2011, pp. 1–8.

[8] J. Valenzuela and M. Mazumdar, "Monte carlo computation of power generation production costs under operating constraints," *IEEE Transactions on Power Systems*, vol. 16, no. 4, pp. 671–677, Nov 2001.

[9] D. Maity, A. Chowdhury, S. S. Reddy, B. K. Panigrahi, A. R. Abhyankar, and M. K. Mallick, "Joint energy and spinning reserve dispatch in wind-thermal power system using ide-sar technique," in *Swarm Intelligence (SIS), 2013 IEEE Symposium on*, April 2013, pp. 284–290.

[10] S. R. Samantaray, L. N. Tripathy, and P. K. Dash, "Differential equation-based fault locator for unified power flow controller-based transmission line using synchronised phasor measurements," *IET Generation, Transmission Distribution*, vol. 3, no. 1, pp. 86–98, January 2009.

[11] M. R. Nayak, K. R. Krishnanand, and P. K. Rout, "Modified differential evolution optimization algorithm for multi-constraint optimal power flow," in *Energy, Automation, and Signal (ICEAS), 2011 International Conference on*, Dec 2011, pp. 1–7.

[12] L. L. Garver, "Transmission network estimation using linear programming," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-89, no. 7, pp. 1688–1697, Sept 1970.

[13] R. Romero, A. Monticelli, A. Garcia, and S. Haffner, "Test systems and mathematical models for transmission network expansion planning," *IEE Proceedings - Generation, Transmission and Distribution*, vol. 149, no. 1, pp. 27–36, Jan 2002.